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Small LTE Base Stations Deployment in Vehicle-to-Road-Infrastructure Communications

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Additional information is available at the end of the chapter

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1. Introduction

Rational and efficient handling of vehicular traffic and people movement is already nowadays a huge challenge that increasingly needs to be supported by dedicated technologies. Scenarios like Smart Cities and Smart Roads are therefore among the most promising areas in which major technological breakthroughs are expected in the next two decades. The delivery of end user services in these scenarios surely call for an ensemble of different technologies to be displaced together; for successful deployment of such technologies and for positive and effective impact on daily life, one of the most important factors is certainly the efficient, fast and flexible distribution of information. The possibility to transmit a large quantity of data is of course necessary in these kind of scenarios, but is not to be separated from the possibility to have higher spectral efficiency and higher flexibility of spectrum configuration. Another key factor is the cost of the network infrastructure, which can easily become a showstopper even for the most promising service or technology. In fact in recent years, vehicle-to-vehicle (V2V) and vehicle-to-road-infrastructure (V2I) communications have attracted great interest for the potentially extended usage in traffic applications and emergency situations. While in the former case the communication system is realized by means of an ad-hoc network (denoted as VANET), in the latter vehicles, i.e. mobile terminals, exchange data packets each other and with the Internet by means of a base station (BS) situated close to the road side. So, in V2I the BS controls the network and manages the connections with and between the vehicles, simplifying the vehicle transceiver and improving performance, including the reliability of emergency communications.

Obviously the cost of the V2I infrastructure is higher and this aspect should be evaluated carefully w.r.t. the performance advantages and the revenue growth for the operators. One of the objectives of the present work is to show how such a network infrastructure can

be already deployed using equipments available for mass production with a high degree of maturity and acceptable costs, thus making Smart Roads deployment economically attractive for operators.

Two solutions are currently object of interest for the V2V and V2I communications: IEEE 802.11p, which is an extension of the IEEE 802.11 standard for local area networks, and the fourth generation LTE (Long Term Evolution) cellular radio system [1–4]. Currently 3GPP LTE system is emerging as the dominant radio access technology for the next 10 to 15 years. It addresses effectively the issues briefly depicted above as it provides effective broadband access and distribution with high spectral efficiency and relatively simple network structure. At the same time, it preserves key features such as high speed mobility, voice services, quality of service, minimal latencies, and high flexibility in the allocation of radio spectrum resources to final users.

Additionally, with reference to the deployment of broadband technologies and therefore also in the case of LTE system, it is nowadays clarified that the role of small cells will be more and more important in order to guarantee real broadband availability for the end users and an higher degree of adaptability of the network to the real geographical and users' density constraints [5, 6]. In other words, next generation networks will have a macro cells layer with the role of making available to the end users the generic access and a micro/small cells layer with the task to take over the higher demand for data rate and coverage in strategic hot spots.

In general, small cell diameter ranges from a few hundred meters to a few kilometers, therefore, for the deployment of a V2I network, it is necessary to locate a quite large number of base stations along the road. Major consequence is that the cost of the base station is to be kept as low as possible. The most important hardware components for this kind of base station are the following:

- One generic processor to handle all Radio Resource Control (RRC), Radio Resource Management (RRM), Operation and Maintenance (OM) and Self Organizing Networks (SON) functionalities.
- Digital Signal Processing (DSP) power to handle Physical layer (PHY) and layer 2 Medium Access Control (MAC), Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP) functionalities. It can be achieved using multicore devices or an equivalent System-on-Chip (SoC).

This kind of configuration is already adopted in several commercial solutions and several examples of the adopted chips can be found in [7–9]. Typically they support LTE 3GPP releases 8 and 9 [10] up to 2x2 MIMO transmission data rate which is up to 150/75 Mbps, respectively for Downlink and Uplink (DL/UL), for $BW = 20$ MHz channelization. The adoption of DSP processors is usually preferred because it eases software development and upgrades. The indicative cost for such equipment including Radio Frequency (RF) board ranges from 1000 to 2500 Euros considered in volumes, which is in line with the need of mass deployment. The whole small base station can be mounted on any existing support, such as light lamps, traffic signals or similar, so that the cost of deployment of a dedicated mechanical infrastructure is massively reduced. This is feasible because the physical dimension of the base station described can be easily in the range of a shoes box without the need to face with special hardware design issues.

In this work we study the application of LTE small base stations on roads characterized by high traffic density, as for example parts of national highways in the proximity of important cities. Small BSs respond to the necessity of obtaining excellent performance without high capital investments and with easy installment (e.g. on the already existing lattices for traffic signaling) and fast auto-configuration. It should be noted that cellular networks, whose infrastructure is already widely deployed, have been proposed several times for vehicular applications especially in the third generation radio network (UMTS). Nevertheless in LTE and in future next generation radio network, heterogeneous and scaled radio stations, covering overlapping areas of different sizes, will be one of the keys for an optimal, from a technical point of view, and cost effective usage of the bandwidth. So next generation LTE small BSs, specifically designed and dedicated only to the road coverage by means of small cells, could constitute a valid, inexpensive option at least for road scenarios characterized by high traffic and user densities.

The main peculiarities of vehicular communications are the considerable high speed of vehicles and the very low latency that must be guaranteed in high priority emergency data transmissions between the different vehicles through the small cell LTE infrastructure. Examples of emergency services are those to avoid car accidents or dangerous situations before the driver recognition and reaction. Moreover, we may add the widespread necessity of ambitious capacity requirements for future broadband wireless network in order to provide high rate capabilities for audio and video stream applications.

So these networks expose system designers to the challenging compromise between the scarcity of spectral resources, the impairments introduced by radio propagation randomness and the stringent service constraints of vehicle communications in case of emergency. At the heart of this challenge there is the ability to manage radio resources as efficiently as possible in all available dimensions (space, time, frequency or channel, power, modulation and coding).

In this work, we investigate three fundamental features for the physical layer of V2I in LTE small cells: the topological layout, including the role of the antenna directivity function, the scheduling strategies for V2I connection performance and the impact of imperfect channel estimation in fast time varying scenarios.

The chapter is organized as follows: Sect. 2 describes the system model, the possible topological distribution of small base stations in the vehicular communications infrastructures, the simulation assumptions and the analysis strategy to highlight the significant design and performance parameters. Sect. 3 reports the fast adaptive strategies adopted in the analysis. Sect. 4 illustrates the numerical results of the system analysis in terms of the global system parameters previously defined, and finally conclusions are reported in Sect. 5 .

2. System model

We started our investigation on Smart Road scenario considering some specific services which may be of real interest for the end users. Such services are then translated into the respective traffic models and afterwards used as an input for the simulations.

1. *High priority traffic:*

- Emergency warnings: this service allows a centralized entity to broadcast or multicast to all the affected vehicles the necessary emergency alerts (low data rate consumption) related to the road scenario itself.
- Emergency calls: this service allows the vehicle to start an emergency call towards public forces, tow trucks, ambulances or also other vehicles moving on the same road.

2. *Medium priority traffic:*

- Traffic information: by this service the end user automatically receives detailed information about the traffic situation; these data are to be broadcasted to all the vehicles and are handled by a central application server. Then each vehicle can analyze and adopt only the information that are consistent with his planned route, taking decision accordingly. This service is considered a low rate, medium priority broadcast/multicast data transmission.
- Weather forecast: this service is similar to the previous one but has a different distribution with reference to the geographical regions in which it is broadcasted.

3. *Low priority traffic:*

- Multimedia services: all the bandwidth remained unused by the previous services will be available for additional services like web browsing, video on demand, VoIP. The transmission of this data is not the primary task of a V2I deployment, but for sure it can bring an added value to the whole infrastructure. For this type of services it is extremely important to apply an efficient scheduling algorithm that may allow a better usage of the remaining available resources.

Having described a bundle of services which are probably the most interesting for the end users, we indicate a number of corresponding LTE features that are to be included in the system to support such services. These important features are then turned into traffic models or general system constraints which are consequently inserted into the simulation work. The goal is to create a link between the real world constraints (given by the network infrastructure, the standard, the services needed by the end users) and our simulation works.

- *Number of supported users:* we hypothesize a small cell would have to support approximately 100 User Equipments (UEs) in the coverage area; these UEs would all be in connected state, i.e. the UE state specified in the standard in which the UE can potentially exchange data with the network and can be paged without requiring the access procedure. Therefore 100 UEs are a reasonable figure for a commercial small cell. This parameter is therefore acceptable and does not represent a limiting factor.
- *Data rate per user:* another key performance figure for a commercial small cell base station is the maximum data rate supported per each user. With a MAC scheduling algorithm of reasonable complexity and channel bandwidth $BW = 20$ MHz, the theoretical limit of the number of users contemporary scheduled on the same subframe is 100 (i.e. the number of the available resource blocks). However a small cell, with reduced complexity and computational power can support around 10 contemporary users. In the low profile scenarios of single antenna or 2 antennas transmission diversity, the whole 75 Mbps data rate allowed by LTE can be divided among the 100 active users, and assuming to serve 10 users per TTI frame, with TTI frame duration of 10 ms, the system allows 750 kbps

constant data rate for each UE. This sounds a very good performance figure allowed with no special demand to the system. The cell size and/or the data rates are obviously to be scaled with the channel bandwidth BW.

- *High mobility receiver*: the base station receiver shall be tailored to sustain at least a user speed of 150 km/h and to avoid interference from the neighboring cells.
- *QoS support*: the support of the different users quality of service is an important key feature and the LTE MAC packet scheduler is the one in charge of taking decisions on how to deal with the priority and resource allocation.
- *Multicast/broadcast*: these features are already specified in 3GPP release 9 [10] and are thought to dramatically save bandwidth in downlink direction when same information are to be broadcasted or multicast at the same time to all or a group of users. In this case, in fact, the same data flow is transmitted only once towards many users at the same time and does not need to be repeated: for example, if a given traffic situation feed is to be transmitted at 50 users at the same time, the 50 transmission resources that would be required by unicast mode are reduced to one.

Next subsections show the simulated network deployment, the assumptions on the structure of the radio frame and the assumptions taken for the analysis.

2.1. Small base stations deployment

The application scenario is a network of small cell sites uniformly distributed on the linear road layout, and separated by a distance d_{BS} , each one dedicated to the coverage of a road sector, as sketched in Fig. 1.

The BSs not only provide V2I communications for the vehicles passing in their coverage area, but they also communicate each other either to broadcast the emergency messages or to backhaul Internet information at the BSs directly connected to core network. In fact, in presence of small cells, to maintain low infrastructure and operational costs, we assume that only some BSs are equipped with a dedicated wired or wireless link to the core network and Internet, while n_{BH} BSs between them operate in Relay Node (RN) mode [11]. We assume to perform an 'In-band' relay solution, operating on the assigned system UL/DL frequencies, meaning that links between the base station and the relay nodes are on the same carrier frequency as the link between the base station and the user equipment i.e. the BS-RN link and the BS-UE link are on the same carrier frequency [12]. Each i -th base station is equipped with two antennas:

- its sectorial antenna, that has to cover the road sector and whose radiation pattern $A_{FW}(\theta)$ has to be optimized to provide high coverage levels, despite the multi-cell layout context under investigation possibly impaired by interference due to frequency reuse factor equal to one. The corresponding radio interface communicates with both the associated mobile UEs and the illuminated adjacent $(i + 1)$ -th BS, transmitting and receiving respectively on the system DL and UL frequencies. The fundamental parameters that define $A_{FW}(\theta)$ are the 3dB beamwidth θ_{3dB} and the beam orientation, set in order to guarantee an external angle θ_{EXT} as defined in Fig. 1.

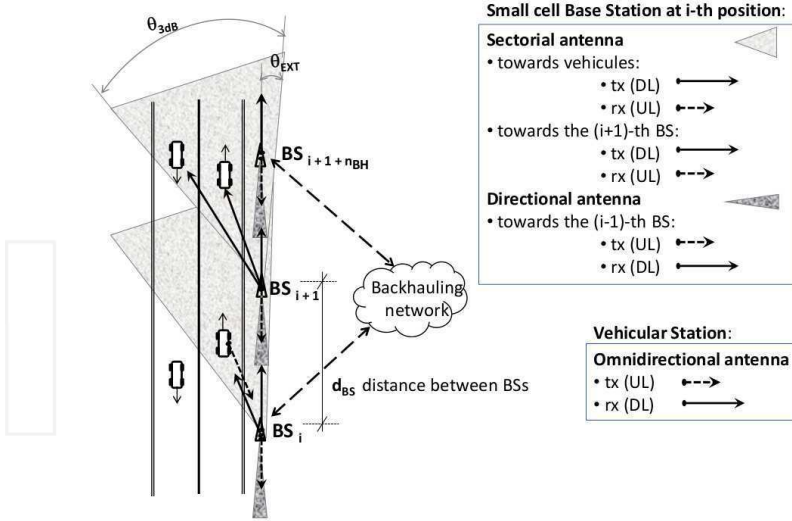


Figure 1. Network topology for smart road applications and vehicular communications. In backward direction, each BS could behave as a UE: for emergency info it transmits on the uplink (UL) and receives on the downlink (DL). For backhauling data it has two alternatives: transmitting on UL or receiving on DL.

- another directional antenna, dedicated to BS to BS (Infrastructure to Infrastructure, or Infra to Infra) communications, so pointing, with a highly selective radiation pattern $A_{BW}(\theta)$ towards the adjacent $(i - 1)$ -th BS, in backward direction w.r.t. the one illuminated by the sectorial antenna. The radio interface associated to this antenna operates as an UE equipment, transmitting on the UL and receiving on the DL.

This communication system topology is chosen in order to make the emergency information flow propagate either forward on the DL, radiated by the sectorial antenna, or backward on the UL, supported by the directional antenna equipment. This responds to the necessity of broadcasting emergency information with very low latency in both road directions. At the same time, the backhaul flow transport can exploit two alternatives:

- in forward direction, so using the sectorial antenna to transmit in DL, and the directional antenna to receive;
- in backward direction, so using the directional antenna to transmit in UL, and the sectorial one to receive .

The choice between the two solutions must take into account the peculiarities of the two traffic flows and the frame structure type, if *Type1* FDD (Frequency Division Duplex) or *Type2* TDD (Time Division Duplex). This topic will be discussed in the next Sect. 2.2.

The V2I communication performance, in the area covered by the sectorial antennas, is simulated selecting, among spatially uniformly distributed vehicles, n_v active mobile users at speed of $v = 130$ km/h in the two road directions at a medium-low inter distance, i.e.

between 25 and 100 m. The gain pattern of the two antennas at the base stations, $A_{FW}(\theta)$ and $A_{BW}(\theta)$, are specified as [13]

$$A(\theta) = -\min(12(\frac{\theta}{\theta_{3dB}})^2, A_m) + G; [dB] \quad (1)$$

where θ is in $[-180, 180]$ degrees range, θ_{3dB} is the 3dB beamwidth in degrees, A_m is the maximum attenuation and G is the antenna gain.

Sectorial antenna parameters will be appropriately adjusted in order to cover the overall road area, minimizing the overlapping regions, possibly impaired by co-channel interference for low values of reuse factor r . On the other hand, mobile terminals are equipped with omnidirectional antennas.

Concerning V2V propagation channel models, due to the high relative speeds involved, especially when we consider vehicles coming from opposite directions on the same route that experience relative speed till to 300 km/h, effects such as strong time variance and non stationarity are particularly pronounced and cannot be neglected. However, unlike V2V propagation, the V2I propagation channel model generally shows great similarity to conventional cellular propagation channels, e.g. macro-cells and micro-cells, for which standardized channel models can be adopted [13]. All of these models provide key parameters to generate the appropriate distributions of path-loss and fading statistics, temporal variance and delay spread as particular scenarios require.

It must be mentioned that a typical V2I scenario along a highway with a fixed roadside transmitter and a vehicular receiver has been faced in [14] through a computationally advantageous implementation based on geometrical considerations, but we expect that in this context a more general channel model is more suitable to investigate the performance of the proposed system deployment. In our simulations the input parameters of the 3GPP SCM ('Spatial Channel Model') [15] have been conveniently initialized to simulate the application-specific scenario covered by LTE micro-cells. An SCM *MicroUrban* scenario (as suggested in [16]) has been used to generate path loss, shadowing and fast fading realizations, with either *LoS* or *NLoS* propagation in order to test the system performance under different propagation severity levels.

Antenna and channel model parameters used in the simulations are summarized in Table 1.

2.2. The frame structure

According to the LTE physical layer, we consider a communication system with an Orthogonal Frequency Division Multiple Access (OFDMA)-based frame structure as shown in Fig. 2, where subcarriers and time-slots are grouped in the so-called Resource Blocks (RB), which are the basis for the radio resource assignment to the users.

Each frame has a fixed time duration $T_f = 10$ ms and is divided in 10 subframes of duration $T_{sf} = 1$ ms, each one of them corresponding to 2 OFDMA slots of 0.5 ms. One OFDMA slot contains 7 symbols (with normal cyclic prefix) or 6 symbols (with extended cyclic prefix). On the frequency domain, the bandwidth BW is divided in N_{sch} subchannels. The channelization considered for the small cell deployment under test will be $BW = 1.4$ MHz, $BW = 5$ MHz

Base station equipment	
Sectorial Antenna Gain G [dBi]	[17 – 30]
" 3-dB beamwidth θ_{3dB} [°]	[15 – 60]
" external angle θ_{EXT} [°]	[3.75 – 15]
" Maximum power [dBm]	46
User station equipment	
Antenna Gain [dBi]	0
Radiation Pattern	omnidirectional
Noise figure [dB]	7
Channel model	
Path loss [dB], d [m]	SCM Urban Micro LoS: $30.18 + 26\log_{10}(d)$ NLoS: $34.53 + 38\log_{10}(d)$
Shadowing [dB]	SCM Urban Micro (LoS: $\sigma_S = 4$; NLoS: $\sigma_S = 10$)
Fast fading	SCM Urban Micro (LoS/NLoS), $v = 130$ km/h
Co-channel Interference model	Explicit (from the co-channel cells)
Cell Layout	
Inter-cell distance d_{BS} [m]	[250 – 1500]

Table 1. Antenna and channel model parameters.

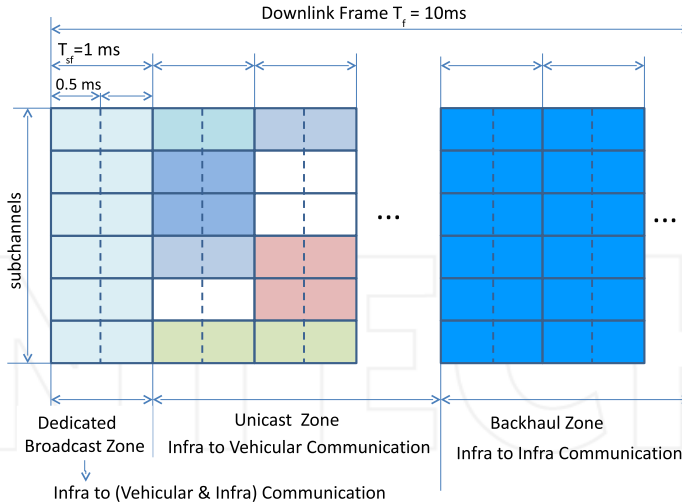


Figure 2. Structure of the downlink frame with three zones dedicated to the following types of traffic flows: Emergency Broadcast information, Unicast communication and Backhauling data produced by the BSs that are not directly connected to the core network.

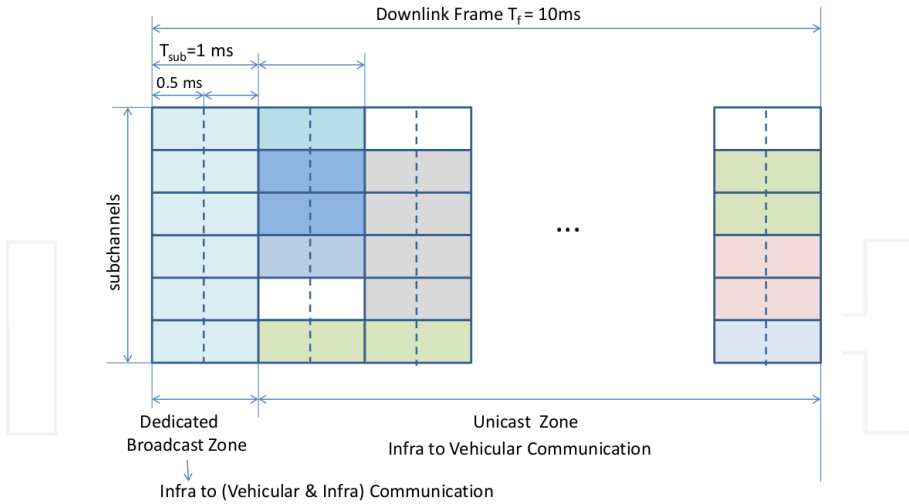


Figure 3. Structure of the downlink frame with two zones, the Emergency Broadcast Zone and the Unicast Zone, assuming that the backhaul flow is transmitted on the UL. Part of the Unicast zone is left free (blank spaces) for respecting the limits on the backhauling capacity when $n_{BH} > 0$.

and $BW = 10$ MHz corresponding to 6, 25 and 50 subchannels. Each subchannel is always constituted by 12 subcarriers. The minimum time-frequency portion to be allocated to a user is one RB, i.e. 1 subframe \times 1 subchannel, providing a modulation rate of 168 or 144 symbols/ms, respectively for normal and extended cyclic prefix.

In the LTE standard two types of frame structure are defined, Type 1 FDD and Type 2 TDD. Both of them could be considered, but we concentrated on the FDD frame structure. The performance results discussed in the sequel will refer to the downlink since it is the most stressed and critical direction in this application. In this context, according to the types of traffic defined in Sect. 1, we assume the following allocation rules:

- emergency information, with the highest priority are allocated in the broadcast zone;
- medium and low priority traffic towards vehicles is allocated in the unicast zone according to a smart algorithm for maximizing the overall capacity on this portion of the time-frequency OFDMA frame. As explained in Sect. 4, this portion will be subject also to limits for respecting the backhauling capacity.
- backhaul information is allocated, with high priority, in portions of the time-frequency OFDMA frame (UL or DL) that can be changed adaptively in each new $T_f = 10$ ms.

We observe also that, while emergency and unicast information are communications between BSs and vehicles, backhauling information are intra-communications, from BS to BS.

As previously introduced in Sect. 2.1, and shown in Fig. 1, the backhauling flow could be transmitted either on the UL frame (using the directional antenna) or on DL frame (using

the sectorial antenna). The adoption of one of the two solutions strongly depends on the capacity and congestion of the two UL and DL directions. These two alternatives provide two different fragmentation of the DL frame, as reported in Figs. 2,3.

In both cases, the key performance factor is the satisfaction of the DL emergency data transmission from BS to the vehicles. The most efficient transmission mode for emergencies information are the broadcast resources being available for the Multimedia Broadcast Multicast Service (MBMS) from 3GPP LTE standard [10]. In this configuration, a single dedicated subframe is reserved on all over the bandwidth (as depicted in Fig. 2). The dedicated broadcast channel covers all the RBs (6 for $BW = 1.4$ MHz channelization) in a subframe, transmitting with a fixed rate of 1 bit/sym. This means that a single emergency message (i.e. occupying one RB per frame) could transport 168 bit/s (normal cyclic prefix), and the ensemble of highest priority messages transmitted on the broadcast zone corresponds to a maximum of 1 kbit/s (always on a bandwidth $BW = 1.4$ MHz).

The second zone in Figs. 2,3 concerns the downlink transmission of unicast traffic flows from BS to vehicles. This is a contention zone, in which Resource Blocks assigned to a user are processed according to its channel quality, benefiting of the adaptive modulation capability included in the OFDMA standard. Adaptive modulation, in fact, allows to choose for each subchannel the most efficient modulation and coding scheme (MCS) supported by the Signal-plus-Interference-Noise-Ratio (SINR) experienced on that subchannel. The modulation and coding profiles considered in the simulations are 5, as reported in Table 2, starting from the most robust one that provides $\eta = 1$ bit/sym rate to the most efficient one corresponding to $\eta = 6$ bit/sym rate. Even if LTE standardizes till to 14 different MCS, it has been verified [17] that such a fine granularity is generally not necessary and a lower number of profiles performs equally well on mobile channels with multiple cells. We emphasize again that, unlike the transmissions of unicast information, the broadcast transmissions of the safety messages are protected using the most robust MCS. Note that, in case of a unicast traffic load less than 100 percent, some RBs can remain not allocated (the blank blocks in the figures), either for not overloading the intra-BSs backhaul or for decreasing the interference realizing a sort of fractional reuse. The role of the resource allocation algorithms (Sect. 3) will be fundamental for managing the time and frequency positions of the not allocated RBs in interfering cells in order to reduce co-channel interference in a multi-cell scenario. The third transmission zone, when present (Fig. 2), is dedicated to the transport of the backhauling flow, activated only for the BSs not directly connected to the Internet: if $n_{BH} = 0$ the backhauling zone is not requested, while for $n_{BH} \geq 1$ the backhauling zone has to be dimensioned at every BS not connected to Internet, considering that the backhauling capacity requirement will increase from BS to BS between two consecutive Internet connections. If the backhaul flow is transmitted on the UL frame, the downlink frame will be segmented into two zones (Fig. 3): more space can be dedicated for the unicast zone in DL, while UL frame will host the backhauling traffic. Considerations on the frame structure type, on the expected volume of backhauling traffic, on the deployment parameter n_{BH} , that influences the backhauling traffic volume, must be taken into account in order to make a correct allocation of the RBs during the BSs operations. The numerical simulations presented in Sect. 4 aim at highlighting the performance limits for a realistic range of the system parameters, summarized in Table 2.

Downlink Air Interface Parameters	
Center Frequency [GHz]	2.0
Bandwidth [MHz]	[1.4, 5, 10]
Number of subcarriers per RB	12
Number of RB / time-slot	[6, 15, 25]
MCS rates [bit/sym]	1, (4 × 1/2), (4 × 3/4), (6 × 3/4), (6 × 4/4)
Frame duration [ms] T_f	10
Subframe duration T_{sf} [ms]	1

Table 2. LTE compliant system parameters.

2.3. Design parameters and performance evaluation analysis

An analysis of the capability of the proposed small base stations layout for a typical smart road, constituted e.g. by a highway, will be developed according to the following phases:

- Definition of a typical traffic scenario between a vehicle and a base station situated at the road side.
- Definition of the parameters for the base stations setup and deployment.
- Definition of the output performance measures of the network.

The traffic scenario will be constituted by a typical highway, of width equal to 24 m and vehicles at constant velocity of 130 km/h. The communication traffic is measured by the number of n_v connected vehicles per 100 m in the highway (Fig. 1). We assume that an emergency broadcast subframe is reserved for each DL time-frame (corresponding to 1/10 of the OFDMA resources) and each active vehicle requires $k_u = 1$ resource blocks per time-frame in the unicast zone for its medium priority traffic. Note that an increase in the number of active vehicles n_v , i.e. the number of RBs to be allocated on the unicast zone, causes also an increase in the backhauling traffic. In particular, one of the limits imposed on the network is given by the amount of traffic that the BSs can transmit on the intra-BSs backhauling without overloading and data losses. We remark that, in the proposed deployment, part of the backhauling will be performed by the same BSs acting as relays (Fig. 1): we have assumed that, when $n_{BH} > 0$, each BS can occupy only a fraction $1/(n_{BH} + 1)$ of the time-frame portion that remains after the broadcast subframe allocation (i.e. 9/10 of the time-frame). This rule prevents from the overloading of intra-BSs backhaul, that is implemented in the UL space (for example in the UL time-frame for the FDD case). As already observed, this unoccupied portion of the DL bandwidth is changed dynamically according to the number of connected vehicles and to their channel conditions.

The deployment analysis will be performed focusing on the following design parameters: the distance d_{BS} between base stations, the number n_{BH} of base stations between two connections with the Internet core network, the sectorial antenna beamwidth θ_{3dB} and external angle θ_{EXT} .

Finally the output performance will be measured by the following parameters:

- Vehicular density n_v , as the number of active n_v vehicles in 100 m simultaneously served (medium priority traffic) with a given outage probability.

- Overall capacity [Mbps] for low priority traffic.

3. Scheduling and allocation techniques for vehicular communications

In OFDMA systems like LTE, smart scheduling and allocation of radio resources are crucial aspects for optimal performance. The allocation techniques are based on the knowledge of the channel state indicators (CSI) for each user and for each subchannel. According to the procedures in LTE standard the updating rates of CSI reports from the users should be comparable with the coherence time of the channel and compatible with the maximum latency admitted in emergency data exchange. This is even more important in this kind of application, characterized by requirements of high priority and low latency of emergency communications. This challenging factors combination constitutes the main limiting factor in these applications [3, 4]. Smart resource scheduling and allocation have algorithm updating rates that are affected not only by the periodicity of the transmission of CSI reports (the minimum admissible period time in LTE is 1 ms), but also by the computing time of the algorithm itself. As we are considering high speed terminals, unforeseen channel variations during the algorithm updating time could cause imperfect algorithm allocations due to imperfect estimation of channel gains. The imperfect estimations of channel state indicator have to be taken into account, since they are expected to have an impact on the effectiveness of scheduling strategies, and great attention should be paid on the refinement of fast updating procedures. The power and channel adaptation approach proposed in [18] showed, in an interference limited multi-cell scenario with high speed mobile users, high performance, simplicity and the fast adaptivity required in the V2I deployment.

We emphasize again that the smart algorithm is not applied for the allocation of the short emergency messages, as this last service can benefit of the dedicated broadcast channel on the whole bandwidth, but for the assignment of RBs to the users on the unicast zone in order to increase the spectral efficiency of the communications between BS and the vehicles so exploiting the benefits of multi-user diversity.

Finally, the smart allocation of RBs, which comprises also the power adaptation, will be crucial for limiting the interference in a multicellular scenario with a low frequency reuse factor, as desirable in cost-efficient network solutions. In this context, the portions of the time-frame not assigned to any vehicle, to avoid overloading the intra-BSs backhauling (blank spaces in Fig. 1), will decrease the co-channel interference also in overlapping coverage areas served by BSs operating all at the same frequency.

4. Numerical results

In this Section, numerical results will be focused on the final coverage, i.e. the number of connected vehicles, the outage probability and the throughput for different selections of the cell parameters (d_{BS} and n_{BH}), algorithm parameters and channel models, including the effect of imperfect channel estimation.

The simulated network is composed by a line of 21 consecutive equi-spaced BSs (d_{BS}). The road used in the simulations has a width equal to 24 m.

As introduced in Sect. 2.2, the backhauling flow among base stations has been realized in the FDD UL bandwidth. Consequently the capacity results are collected in the DL, according to

the frame structure in Fig. 3. As already observed in Sect. 2.3, this choice requires a limit on the downlink frame occupation for not overloading the backhauling allocations.

In the next Sect. 4.1, we present the results on the sector configuration in terms of antenna parameters and distance between adjacent base stations in order to select the most appropriate geometric parameters for the V2I scenario. Here the numerical results are derived in terms of average SINR (Signal-to-Interference Noise Ratio), i.e. without the contribution of shadowing and fast fading. Then the two dynamic Micro Urban scenarios have been tested, LoS and NLoS respectively. So Sect. 4.2 and 4.3 report the capacity results, expressed by the average density of vehicles that can be served with medium priority and the available low priority throughput, obtained averaging the capacities of the 21 sectors. The allocation of the radio resources is realized by the following steps: first the RBs dedicated

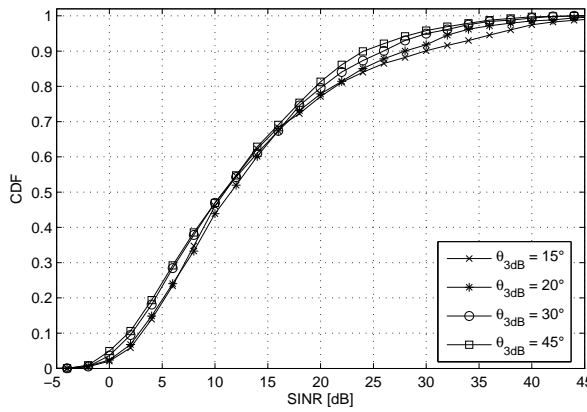


Figure 4. Cumulative distribution function of the average SINR for uniformly distributed vehicles in the 21 cells layout (LoS path loss model, $\theta_{EXT} = 7.5^\circ$ and $d_{BS} = 500$ m).

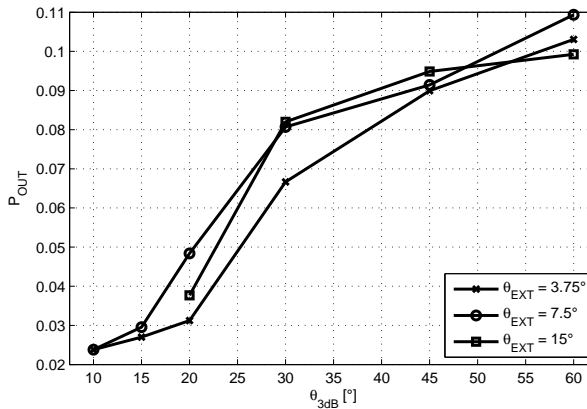


Figure 5. Outage probability as a function of θ_{3dB} for uniformly distributed vehicles in the 21 cells layout and different θ_{EXT} (LoS path loss model and $d_{BS} = 500$ m).

to the broadcast transmission of high priority emergency communications are allocated in each time-frame, then a single RB is assigned to each medium priority data request. This last value returns the number of vehicles that can exchange medium priority data, such as road and traffic conditions. These medium priority RBs can transmit using one of the available modulation profiles, according to the SINR at the vehicle. The resource allocation is performed by means of algorithms that exploits the multi-user diversity, represented by the diversity indicator I_D [18]. Finally the rest of the available bandwidth is used for the low priority Web and Multimedia services. A part of the RBs in the DL frame is left free because of (i) the necessity of not overloading the bandwidth required for the backhauling and (ii) the necessity of realizing a sort of fractional reuse in order to limit the interference among base stations. In fact, we assume that all the base stations use the same frequency achieving a potential reuse factor equal to 1. In the results presented here, the bandwidth is used for a portion between 0.4 and 0.7 according to the parameter n_{BH} , i.e. the number of base stations that are required to accumulate and forward the backhauling traffic.

Except for the results in Fig. 10, a fading margin FM equal to 10 dB has been always included in the SINR computation during the RBs assignment process in order to limit the impact of channel estimation errors, interference and fading variations.

4.1. Sector configuration

The study of the sector configuration is focused on two fundamental parameters of our scenario and it is preliminary for the successive capacity results. Since this particular scenario is characterized by a line of consecutive base stations, we are interested in the antenna beamwidth and the base stations inter-distance that are compatible with the BS transmit power and the received SINR at the locations of vehicles moving along the road. For this reason we have computed the average measured SINR along the road and the outage probability according to the space loss propagation for different distances between the vehicles and the BSs locations.

The antenna aperture is assumed as the 3 dB beamwidth (θ_{3dB}) in the 3GPP directivity function and the antenna gain is set according to this variable beamwidth. Here the particular layout of the small cell, that should cover a portion of the road, requires a narrow antenna beam for limiting the interference impact on other cells operating at the same frequency. In addition, each antenna covers also the next BS for backhauling purposes and the boresight is set in order to guarantee an external angle equal to θ_{EXT} , as shown in Fig. 1. The geometrical layout, the antenna and the path loss models are used for computing the average SINR experienced by all the vehicles uniformly distributed on the road; each vehicle is assigned to the cell, or base station, that guarantees the best average $E[SINR]$ and the outage P_{OUT} is defined as the probability that $E[SINR]$ is below the lowest threshold profile (Table 2).

In Fig. 4 it is possible to see the $E[SINR]$ cumulative distribution function obtained with different θ_{3dB} ; results are similar for the NLoS path loss model and for different BS distances $250 < d_{BS} < 2500$ m. We may observe that (i) $E[SINR]$ does not depend significantly on d_{BS} at the distances under analysis, since the system is interference limited (not noise limited), and (ii) $E[SINR]$ improves slightly for θ_{3dB} approaching 15° . This is confirmed by Fig. 5 where P_{OUT} is reported as a function of different θ_{3dB} and θ_{EXT} . According to these geometrical results, a beamwidth $\theta_{3dB} = 15^\circ$ with a boresight that guarantees $\theta_{EXT} = 7.5^\circ$ is chosen for the capacity simulations of the next Sections.

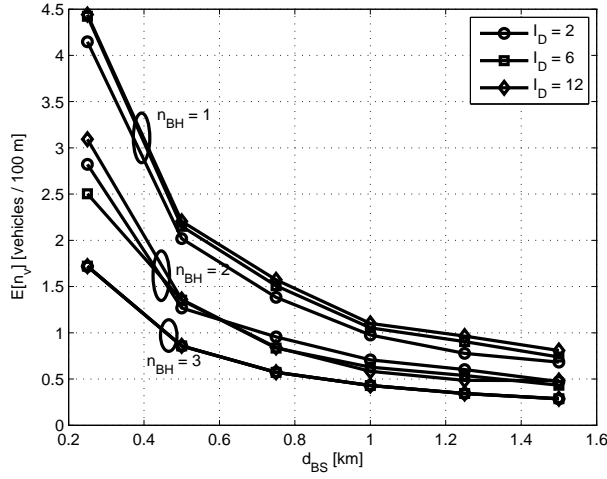


Figure 6. Average vehicles density supported in each subframe T_{sf} as a function of BSs distance for different n_{BH} in the 21 cells layout (SCM LoS channel model, 5 MHz).

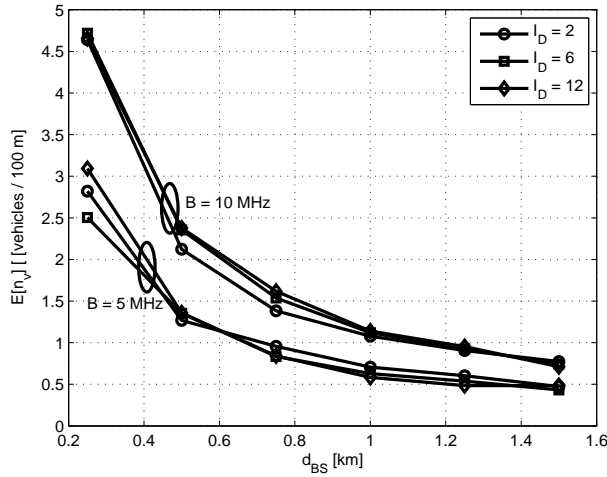


Figure 7. Average vehicles density supported in each subframe T_{sf} as a function of BSs distance for different bandwidths in the 21 cells layout (SCM LoS channel model, $n_{BH} = 2$).

4.2. Scenario 1: SCM Micro Urban LoS

Numerical results are obtained averaging 100 independent fast fading realizations of the SCM Micro Urban LoS and NLoS channel models and each realization represents the evolution of the channel on 10 time-frames for a total time equal to 100 ms. For each realization, it is simulated the behavior of the system in each of the 100 consecutive subframes and in each of the 21 sectors taking into account, obviously, the mutual interference generated on

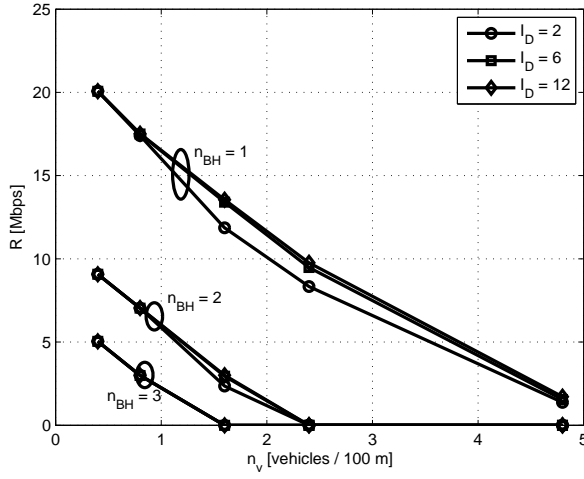


Figure 8. Average low priority throughput as a function of the vehicles density for different n_{BH} in the 21 cells layout (SCM LoS channel model, $d_{BS} = 500$ m, 5 MHz).

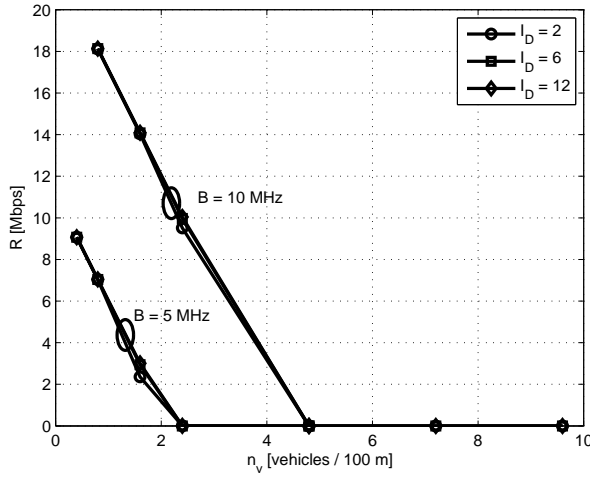


Figure 9. Average low priority throughput as a function of the vehicles density for different bandwidths in the 21 cells layout (SCM LoS channel model, $d_{BS} = 500$ m, $n_{BH} = 2$).

the receivers side by all the 21 downlink signals. We remark that the effective reuse factor is greater than 1 since only a fraction of the available RBs is reserved to data traffic for not overloading the backhauling. We observe that, if the fraction of used RBs is $1/(n_{BH} + 1)$ (Sect. 2.3), the effective reuse factor is equal to $n_{BH} + 1$; however we remark that this bandwidth portion is not static but it is selected dynamically according to the SINR experienced by the vehicles and the number of connected vehicles. High priority traffic for emergency situations

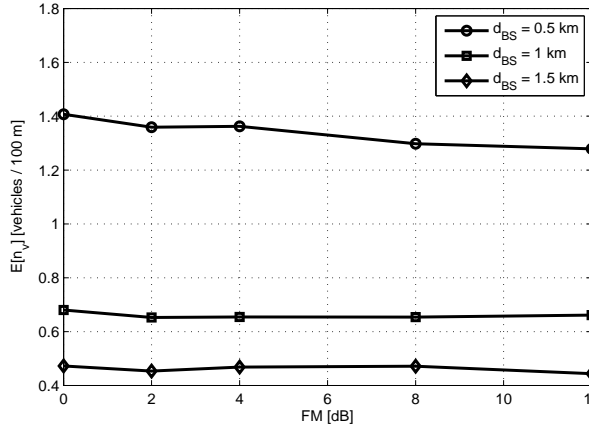


Figure 10. Average vehicles density in each subframe T_{sf} as a function of the fading margin applied to the modulation profile thresholds for increasing robustness against channel estimation errors (SCM LoS channel model, 5 MHz, $n_{BH} = 2$).

is assigned to the broadcast channel, composed by the subframe (all the RBs) at the beginning of each time-frame.

Medium priority traffic is solved by assigning a single RB to the connected vehicles. This assignment is done according to the SINR conditions at each user and hence exploiting the multi-user diversity. The simulation results refer to an outage probability P_{NA} defined here as the probability of not being assigned any RB in a generic subframe. This measure constitutes an upper bound for the probability that a vehicle will not be assigned a RB within the coherence times of channel and interference.

Fig. 6 reports the average number $E[n_v]$ of vehicles per 100 m and per each subframe as a function of d_{BS} and respecting the constraint of receiving an RB for medium priority traffic and a $P_{NA} = 0.01$: it can be observed how the decrease of the density $E[n_v]$ is mostly given by the increasing value of d_{BS} . In the same Fig. 6 it can be appreciated the impact of the wired backhauling access period n_{BH} on $E[n_v]$ while, in Fig. 7, the impact of the bandwidth. If we assume that the time period between two allocations for the same vehicle is equal to N subframes (for example $N = 10$ for a time-frame), the values of $E[n_v]$ reported in the graphs should be multiplied by N for obtaining the number of vehicles, in 100 m, that can be connected and served by the system. So, from these results, it is also possible to appreciate the maximum delay acceptable between two consecutive medium priority RBs.

Low priority traffic is assigned, in a best effort way, to the remaining available RBs after the allocation of the broadcast channel and all the RBs for medium priority traffic. The amount of the traffic available for Web browsing and Multimedia services is represented by the available residual capacity. Figs. 8 and 9 report the low priority traffic as a function of the density n_v of connected vehicles for different n_{BH} and bandwidth values. It is clear that low priority traffic is available when the number of RBs assigned with medium priority is lower than the maximum compatible with the available bandwidth.

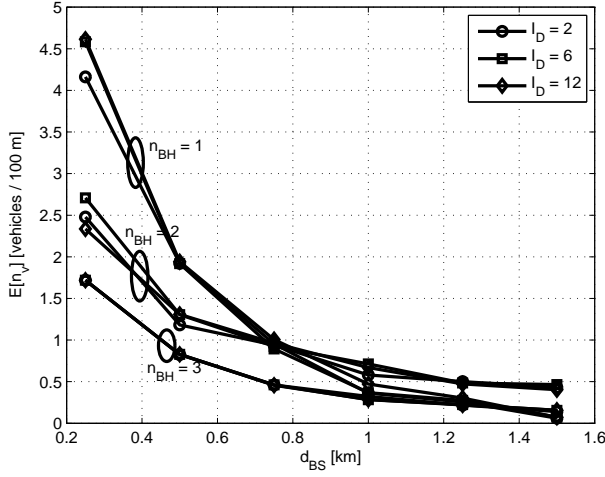


Figure 11. Average vehicles density in each subframe T_{sf} as a function of BSs distance for different n_{BH} in the 21 cells layout (SCM NLoS channel model, 5 MHz).

We can also observe that multi user diversity, represented by the factor I_D , has not a great impact on performance since its effect is limited by the fairness mechanisms introduced for guaranteeing the maximum number of vehicles connected with just one medium priority RB.

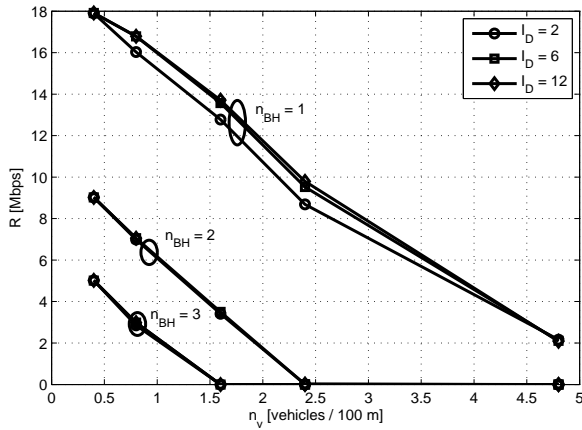


Figure 12. Average low priority throughput as a function of the vehicles density for different n_{BH} in the 21 cells layout (SCM NLoS channel model, 5 MHz).

Finally, Fig. 10 is dedicated to the evaluation of the fading margin impact on the performance: fading margin is used against the variations of interference and channel, including estimation errors, w.r.t. the CSI used at the BSs for the allocation procedures. We observe that a fading margin around 10 dB, generally sufficient for including the channel estimation imperfections,

does not affect seriously the density of vehicles that are served in the system. This result is due to the values of SINR at the vehicles, which are generally high w.r.t. the low modulation profiles that can be assigned to the RBs with medium priority.

4.3. Scenario 2: SCM Micro Urban NLoS

Results obtained for the SCM Micro Urban NLoS channel model are equivalent to those presented in the previous Sect 4.2. From Figs. 11 and 12 it may be observed that, as expected, (i) performance is slightly worse than in the LoS case and (ii) performance decreases more severely as d_{BS} increases.

5. Conclusions

In this work we have studied the deployment of LTE small base stations along roads characterized with high traffic density in order to provide vehicle-to-infrastructure (V2I) communication services. Results have been provided to address the V2I deployment and the set-up of the geometric configuration distinguishing different classes of traffic in the system, from high priority, associated to emergency situations, to medium and low priority services like weather forecast, traffic situation and other multimedia services. Numerical results show that the system, with a proper use of the LTE relay capabilities for the backhauling between adjacent base stations, can provide interesting results for a cost effective deployment of vehicle-to-infrastructure communications.

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